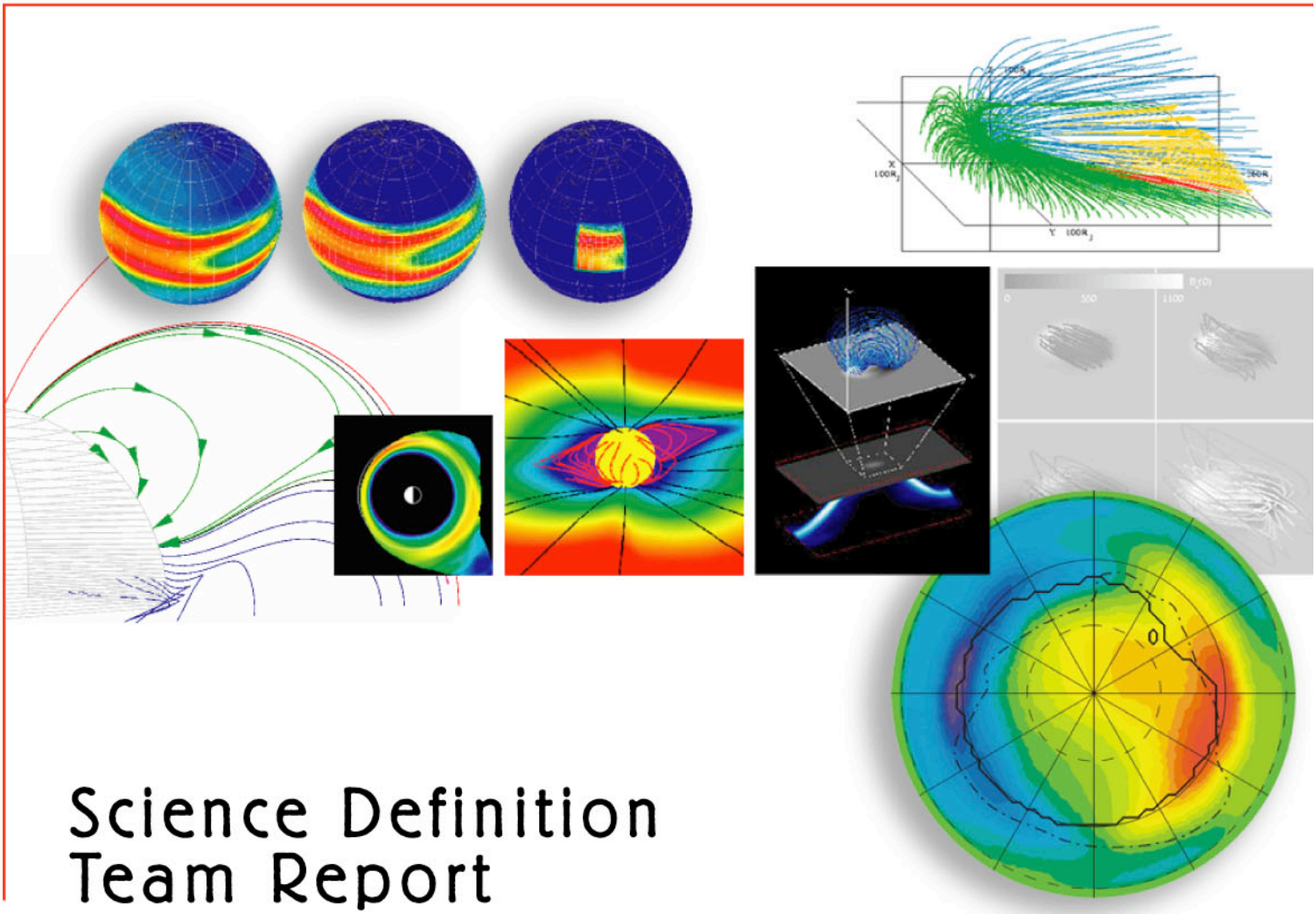
LWS Targeted Research and Technology



Science Definition Team Report

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National Aeronautics and Space Administration

Targeted Research and Technology Within NASA's Living With a Star Program

Report of the Science Definition Team

Targeted Research and Technology Science Definition Team

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EXECUTIVE SUMMARY

Targeted Research & Technology (TR&T)

NASA's Living With a Star (LWS) initiative is a systematic, goal-oriented research program targeting those aspects of the Sun-Earth system that affect society. The Targeted Research and Technology (TR&T) component of LWS provides the theory, modeling, and data analysis necessary to enable an integrated, system-wide picture of Sun-Earth connection science with societal relevance. Recognizing the central and essential role that TR&T would have for the success of the LWS initiative, the LWS Science Architecture Team (SAT) recommended that a Science Definition Team (SDT), with the same status as a flight mission definition team, be formed to design and coordinate a TR&T program having prioritized goals and objectives that focused on practical societal benefits. This report details the SDT recommendations for the TR&T program.

Need for TR&T

The Sun is the primary driver of our complex Sun-Earth system and is also a variable star. Solar variability produces changes in Earth's climate that may compete with those produced by anthropogenic effects and also produces significant changes in the charged particle and electromagnetic field environment of the ionosphere and near-Earth space in ways not yet understood. Variability in the latter on a time scale of hours and days is commonly referred to as "space weather," while on longer time scales it is called "space climate." Both space weather and space climate adversely affect the performance and reliability of certain satellite and ground-based technologies and can endanger human health and life.

Unique TR&T program elements

The SDT had concluded that the following are essential for a successful TR&T program:

- **Target Prioritization**. Specific science targets will most efficiently move LWS toward the goal of understanding the Sun-Earth system for the benefit of society. Initial research priorities for the program have been identified by the SDT and can be found in Sections 2 and 3 of this report.

- **Deliverables and Schedules.** The delivery of research products will determine the success of the program. All proposals for TR&T funding must define the products they will deliver and a timetable for producing them.

- **Cross-Disciplinary Research.** Research that crosses traditional science discipline boundaries is needed to provide a full understanding of the connected Sun-Earth system.

- **Strategic Capabilities.** Models that link the Sun-Earth system have the character of infrastructure for TR&T and are identified as *strategic capabilities* that need to be emphasized and fostered.

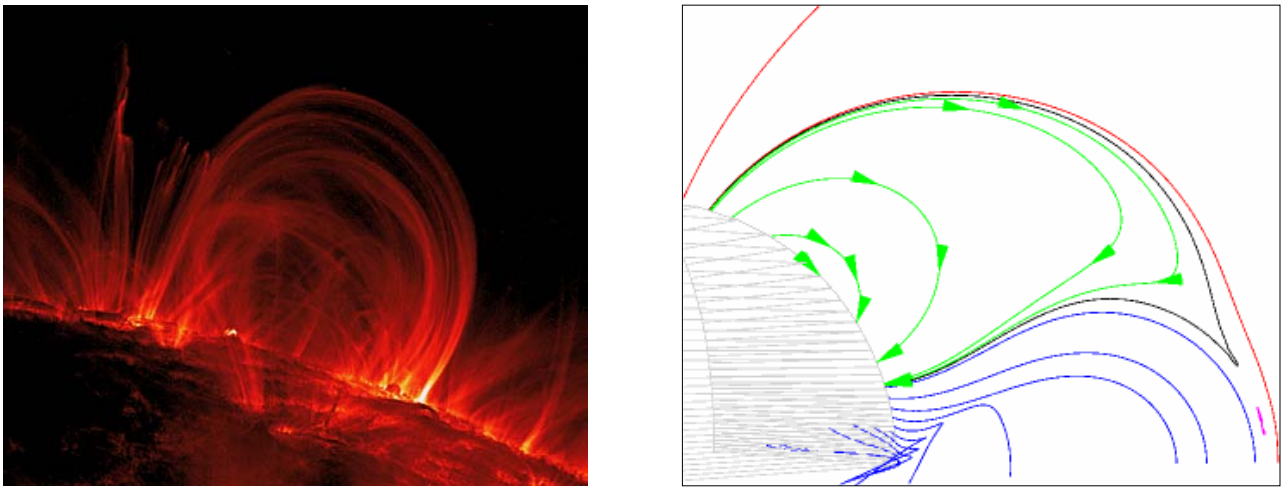


Figure 1. Left – TRACE image of an active region magnetic arcade in the corona. Right – MHD model of coronal magnetic field prior to a CME.

Implementation of the TR&T program

To implement the TR&T program the SDT recommends the establishment of two management elements.

First, a TR&T Steering Committee (TSC), with broad science and application community representation and with rotating membership, to advise and support NASA Headquarters in:

- Establishing and continually updating targets and top-level priorities;
- Measuring the progress of the program in meeting science goals and objectives; and
- Providing mechanisms for monitoring how well products that result from the program are transferred into societal benefits.

Second, a TR&T Project Scientist, with the responsibilities of:

- Representing the TR&T mission/program to NASA Headquarters and the LWS Mission Operations Working Group (MOWG).
- Supporting the work of the TR&T Steering Committee.
- Tracking the progress of knowledge and capability growth in the program.
- Determining the compliance of individual TR&T-funded projects with appropriate metrics, milestones and deliverables.
- Ascertaining that TR&T research products are made available for transitioning to users, where appropriate.

The SDT suggests that successful implementation of TR&T depends on the adoption of the following principles:

- Support data analysis and the development of theories and models that directly address TR&T priority targets, and that have potential societal benefits;
- Require all TR&T-supported activities to identify deliverables with clear relevance to the program's goals and establish schedules and milestones for delivery;
- Give particular emphasis to cross-disciplinary research;
- Support synergistic activities such as workshops and summer schools to facilitate cross-disciplinary activities and to foster the development of a personnel infrastructure for Sun-Earth connection science;

- Support the development of certain *strategic capabilities* that have broad potential use for science and application;
- Support model testing and validation;
- Support technology and data environment development relevant to LWS goals and objectives; and
- Support both small and large research proposals.

Further recommendations

The SDT further recommends that:

- TR&T coordinate with and exploit existing national programs and assets in Sun-Earth system science;
- Infrastructure for the TR&T program be kept to a minimum - the SDT has assumed the existence of an integrated LWS data environment and modeling center capability that will be separately funded outside of the TR&T program;
- The fundamental component of the TR&T mission be projects that are openly competed annually, wherever feasible, including the data environment and modeling center capability if separate funding for them fails to materialize;
- Scientific results arising from TR&T funding be published in the refereed literature;
- Models, tools, and data sets funded by TR&T be preserved for future research and application, primarily via delivery to modeling and/or data centers;
- Modeling and data centers be tasked with facilitating the transfer of appropriate research products to NOAA, DoD, and industry;
- Announcements of Opportunity and decisions on funding reflect TR&T priorities and include the development of *strategic capabilities*;
- Large modeling activities that address coupling across traditional science domains in the Sun-Earth chain specifically be included as *strategic capabilities*;
- Proposals for *strategic capabilities* be competed separately;
- Every TR&T proposal review panel include one or more members who are potential users of the program's products;
- Proposals be ranked on the basis of scientific merit, perceived value to the TR&T mission and its targeted priorities, the description of a credible set of deliverables, success metrics and milestones, and the track record of the proposers;
- NASA Headquarters explore all pertinent funding mechanisms for TR&T-supported research, including Cooperative Agreements and Contracts; and
- Serious consideration be given to funding large, strategic model development efforts on time cycles longer than three years.

1.0 INTRODUCTION TO REPORT

1.1 The LWS Program

The Living With a Star (LWS) initiative fulfills a unique role within the Sun-Earth Connection (SEC) program at NASA as a systematic, goal-oriented research program targeting those aspects of the Sun-Earth system that directly affect life and society. The objectives of LWS will advance research in Sun-Earth system science to new territory, producing knowledge and understanding that society can ultimately utilize.

The objectives of LWS, defined with the above overarching goals in mind, are:

1. Identify and understand those aspects of solar variability that have societal consequences, including the habitability of Earth, the use of technology and the exploration of space;
2. Identify and understand how Earth's climate, upper atmosphere and space environment respond to solar variability on a variety of time scales;
3. Quantitatively connect and model solar variability and the above terrestrial responses to enable substantial improvements in climate and space weather forecasting on multiple time scales; and
4. Extend our knowledge and understanding in the above areas to explore extreme solar-terrestrial environments and implications for life and habitability beyond Earth.

In order to achieve these objectives, it will be necessary to integrate research and development across traditional discipline boundaries of Sun-Earth system science.

Reflecting these objectives, the LWS research program is organized by the two, system-wide themes of the solar role in climate and space weather. LWS success relies on a combined program of observations, theory, and modeling to develop the required comprehensive understanding of the connected Sun-Earth system. The interplay between measurements and models envisaged in this approach is critical to the above objective of integrating research and development across traditional discipline boundaries. LWS therefore consists of two components: flight missions, providing solar (Solar Dynamics Observatory, SDO), heliospheric (Sentinels), and geospace (Radiation Belt and Ionospheric Storm Probes) observations, and a Targeted Research and Technology (TR&T) program providing complementary theory, modeling and integrated data analysis. The central role of TR&T in integrating scientific output, data, and models from LWS and other providers to generate a system-wide picture of Sun-Earth connection science is illustrated schematically in Figure 2. TR&T also encompasses a technology development program that includes instrument development for future LWS missions.

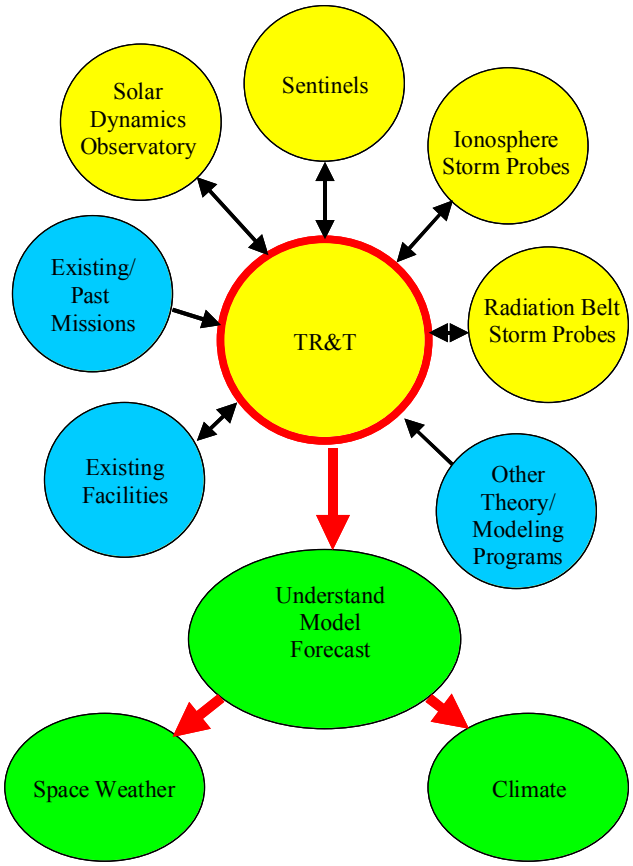


Figure 2. Role of the Targeted Research and Technology program within the Living With a Star program. TR&T will provide both focus and integration for research involving LWS flight missions, flight missions from other programs, and for theory and modeling activities outside of those supported by LWS. The TR&T program will produce scientific understanding targeted at our ability to model, specify and forecast solar variability effects on climate, stratospheric ozone and near-Earth space weather.

1.2 Targeted Research and Technology

The novel and central role of TR&T within a major initiative like LWS mandates careful planning of the programmatic structure as well as the implementation and prioritization of TR&T activities, including milestones and verification of TR&T accomplishments and their relevance. Dependent on the present level of scientific understanding and perceived opportunities for making tangible progress, TR&T should focus its resources on specific questions, specific types of models or combination of models, and on particular data sets needed for model verification or assimilation. In addition, TR&T should support basic research investigations that address open science questions of relevance to LWS. While the data provided by LWS missions are a key element in this endeavor, TR&T needs to incorporate other available data sets, as well as models developed under different programs, in order to meet its science objectives in a cost-effective manner and on a time-scale consistent with program goals. Finally, although the development of operational models is not a direct goal of the TR&T program, TR&T does require mechanisms for transferring knowledge as well as empirical and physics-based models of the Sun-Earth system to potential users of these products. Users include other scientists, policy makers, US agencies charged with developing

operational models for climate/ozone and space weather specification (or "nowcasting") and forecasting, as well as commercial interests such as the airline and power industries.

The near-term research priorities described in Sections 2 and 3 reflect priorities set within the LWS program as a whole, weighted by an assessment of areas where rapid progress is thought to be possible. They also reflect the need to support systematic progress toward the critical long-term goals of developing physics-based predictive capabilities and knowledge of the physical pathways linking solar variability and climate/ozone change, space weather and space climate.

A well-planned, mission-like approach to TR&T implementation and execution is required to maximize TR&T value and productivity and, by implication, to facilitate LWS success. TR&T constitutes a new, unique opportunity to create results and products of demonstrable and lasting value, not only to the advancement of human knowledge, but also to the direct benefit of human society.

2.0 THE ROLE OF SOLAR VARIABILITY IN CLIMATE AND STRATOSPHERIC OZONE CHANGE

2.1 Introduction

The Sun is the primary source of energy for almost every aspect of the natural environment of the Earth, including the climate and our protective ozone shield. Changes in the energy that the Sun emits and the Earth receives, particularly in the near ultraviolet (UV), visible (VIS) and infrared (IR) portions of the solar spectrum, can have a direct effect on the regional and global climate of the planet. The highly variable UV component of the Sun's spectrum directly affects the concentration of ozone in the stratosphere, while both solar radiative and particle fluxes produce changes in the directly exposed upper atmosphere of the Earth that are thought to affect the climate below.

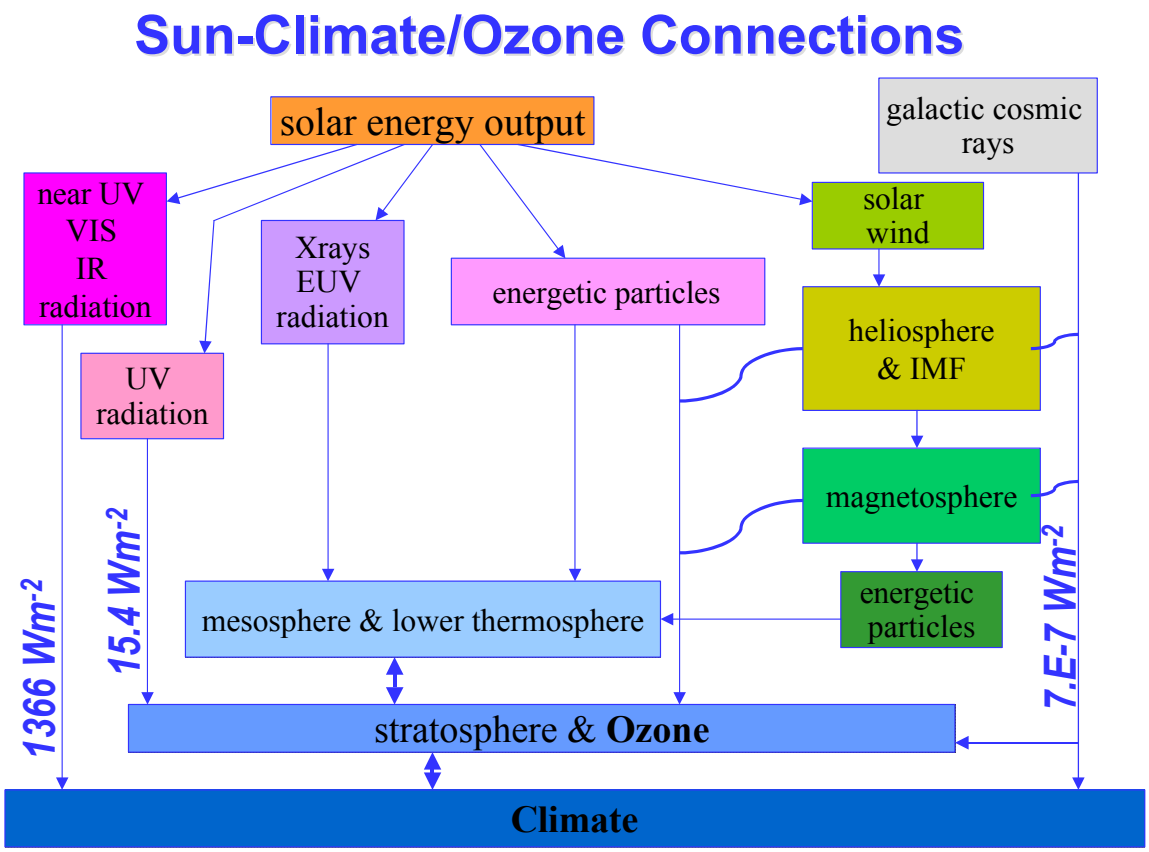


Figure 3. Diagram illustrating linkages between the Sun and different regions of the Earth's atmosphere. Changes in the solar output ultimately influence stratospheric ozone and climate.

The practical question is not whether solar variations affect the climate or the chemical composition of the stratosphere, but rather lies in determining the importance of solar variations relative to anthropogenic and geophysical factors in perturbing the middle and lower atmosphere. Meaningful answers obviously demand reliable knowledge of how much the solar outputs vary, how they have varied in the past, and how the climate system and ozone layer have responded.

The connections between the Sun and climate/ozone are illustrated in Figure 3. The bulk of the Sun's energy in the form of visible, infrared, and near UV radiation (1366 Wm^{-2}) reaches the climate system (troposphere, land surface, ocean). Slightly more than 1% of the UV (15.4 Wm^{-2}) is absorbed in the stratosphere, and even smaller amounts of energy are deposited in the Earth's atmosphere through X-rays, extreme ultraviolet (EUV), and energetic particles. A minuscule amount of energy (7×10^{-7} Wm^{-2}) from galactic cosmic rays reaches the lower atmosphere.

2.1.1 Climate change

Climate change attribution and prediction on multi-year time scales have proven to be difficult because of the complexity of the climate system and the number of factors that affect it. These include, among others, ocean circulation, volcanism, clouds and aerosols, solar variability, and the impacts of human activities. Recurring events such as the El Niño/Southern (Ocean) Oscillations (ENSO) that originate in the South Pacific Ocean, and the North Atlantic Oscillation (NAO), also contribute significantly to climate variability.

It has long been recognized that changes in solar irradiance potentially have significant climatological effects. More recently, it has been proposed that cloud cover, and hence albedo, may be directly affected by cosmic rays, which are modulated by solar activity. Moreover, solar variability affects the climatology and chemical composition of the stratosphere. This raises the question of the role that solar variations play in perturbing the middle and lower atmosphere and their importance relative to other processes, including those of anthropogenic origin, and the impact of stratospheric-tropospheric coupling on climate. Continued progress in understanding climate and in attributing the causes of climatic change requires knowledge of all potential forcing mechanisms, including solar effects. Meaningful answers will depend on reliable knowledge of how much solar outputs vary. The capability to account quantitatively for natural changes due to agents within the atmosphere, anthropogenic sources and solar influences promises to be of immense value to the understanding and assessment of climate evolution.

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), entitled "*Climate Change 2001: The Scientific Basis,*" concluded: "most of the observed warming of the last fifty years is likely to have been due to the increasing greenhouse gas concentrations." But IPCC also recognized that solar variability likely contributed to global warming in the first half of the twentieth century. Reliable quantification of multi-decadal climate change caused by anthropogenic factors is only possible when the natural climate drivers are fully understood. Improving what we know about the Sun's influence on climate is essential for improved understanding and prediction of climate change. A current impediment to the reliable determination of future climate change is our inability to identify unequivocally the cause of change in the recent past (since about 1880 when a number of instrumented, meteorological records were initiated). This task is hindered by the poor knowledge of most climate forcings, including solar irradiance variations, for much of that time period.

2.1.2 Stratospheric ozone change

The importance of stratospheric ozone, commonly known as the "ozone layer," in shielding life on Earth from harmful solar ultraviolet radiation has been recognized for many decades. As with climate change, periodic international assessments of the stratospheric ozone shield have focused on the impact of gases released by human activity – in particular halogens and chlorofluorocarbons - on its abundance, especially the observed ozone depletion since about 1980. The report entitled "*Scientific Assessment of Ozone Depletion: 2002*" sponsored by the World Meteorological Organization (WMO) and the United Nations Environmental Program concluded: "the vertical, latitudinal, and seasonal characteristics of changes in mid-latitude ozone are broadly consistent with the understanding that halogens are the primary cause." And as with climate change, uncertainties arise because of inadequate understanding of the Sun's role in ozone variability. The influence of solar variability on stratospheric ozone was also discussed in the latest WMO assessment and included modeled simulations of the solar UV fluctuations over solar cycle time periods. As a result of international regulations limiting the production of halogens, it is expected that ozone will recover slowly over the next 50 years. An understanding and quantification of the natural changes in ozone variation over this period, including the effects of solar variability through fluctuations in its electromagnetic and particle outputs, will be especially important in verifying the extent to which this recovery is actually occurring.

2.1.3 Recent Progress in Understanding

In recent years an increasing number of studies have built a strong case for significant connections between solar variability and various parameters pertaining to both climate and ozone. The following examples are of particular note: (1) the unambiguous determination of the extent to which variations over a solar cycle control the quantity of ozone in the upper stratosphere, and the demonstration of probable links between stratospheric ozone and circulation in the lower atmosphere; (2) evidence for an eleven-year signal in ocean surface temperature, and in land and tropospheric temperatures, fire, and drought; (3) extensions of what is known of the limits and nature of past solar variability through analysis of ^{14}C in tree-rings, ^{10}Be in ice cores, and the interpretation of these proxy indicators of past solar activity in terms of past solar irradiance changes; (4) comparisons of this new and longer record with contemporary and paleoclimate data from around the world (on land and in the ocean), spanning the full 11,000 years of the present post-glacial era, and especially in the recent Holocene; and (5) the inclusion and testing of solar forcing in climate general circulation models and models of the stratosphere. These examples demonstrate the potential, practical results of more intensive, focused Sun-Climate and Sun-Ozone research. They also help to define the major goals for LWS efforts in these research areas, and to illuminate the gaps in our knowledge that now limit progress.

2.2 Knowledge Gaps

We presently do not know the ways in which the Earth's climate and ozone layer change, regionally and globally, with time. Before we can draw meaningful conclusions regarding possible relationships, we need to know the sensitivity of regional and global climate, as well as the ozone layer, to changes in the solar output of various kinds, including the magnitude of the solar output changes on multiple time scales. Equally important, we need to understand fully the expected impacts of non-solar drivers of climate and the ozone layer, since recorded variations in climate/ozone reflect the net effect of many influences.

2.2.1 Climate change

Throughout the Earth's atmosphere, climate cycles lasting months, years, decades and longer have been identified, and many have periods in common with solar activity – for example, at 11-, 80-, and 210-years. But the driving mechanisms for climate and climate change are not adequately understood. From what we now know of the coupled climate system, many physical mechanisms, linear and non-linear, solar and non-solar, are likely operating simultaneously. Among the solar effects, surface temperatures may change regionally or globally in response to variations in direct heating by solar visible/near IR radiation, and they may also respond to solar-forced internal oscillations (such as ENSO or the NAO). UV-induced stratospheric influences may additionally be superimposed, as may the effects of cosmic rays and electric fields. Of the many influences on climate, only the greenhouse gases are relatively well specified. Others, including solar variability and changes in volcanic and anthropogenic aerosols, are relatively poorly known.

2.2.2 Stratospheric ozone change

Solar variability, changes in greenhouse gases, and changes in volcanic and anthropogenic aerosols also influence the stratosphere, altering temperatures, chemistry and dynamics, which affect ozone abundance. In turn, stratospheric ozone variations may contribute additional tropospheric changes. The stratosphere is not isolated from the upper atmosphere either and we also need a fuller

knowledge of the ways through which the thermosphere and mesosphere, where EUV and X-ray photons and most solar particles are absorbed, may be connected to the stratosphere.

2.2.3 Prediction of climate/ozone change

The climate and stratosphere are not isolated systems, either from each other or from the overlying atmosphere. The physical mechanisms for many of the empirical connections between the climate and stratospheric ozone are only poorly known at present. There is a need for focused interdisciplinary efforts to comprehend and quantify this part of the Sun-Earth connection.

In order to improve the accuracy of climate change and stratospheric ozone depletion predictions and to interpret past variations, we must be able to specify and/or predict the expected course of solar activity and solar output variations on time scales longer than that for which actual observations exist – centuries and millennia into the past, and decades into the future.

2.3 Research Priorities

2.3.1 Climate change

> *Societal Consequences:* Solar variability produces changes in global and regional climate that may compete with those produced by anthropogenic effects.

Problems and Needs: Despite numerous Sun-climate correlations and common Sun-climate cycles, it is not yet possible to specify the "expected" global and regional signatures of solar-induced climate change. We cannot begin to explore physical Sun-climate processes until we are confident of how climate responds to solar variability. Therefore, a synthesis of existing empirical evidence for significant Sun-climate connections is needed to produce a coherent understanding of regional and global impacts.

Current climate models are hard-pressed to account for observed Sun-climate correlations, in particular the empirically deduced solar cycle variations of order 0.1^{o}C in Earth's recent global temperatures. Presumably the models lack (or incorrectly parameterize) the relevant physical processes, including proposed non-linear climate responses to solar forcing that may involve internal climate oscillations. To investigate Sun-climate processes properly, climate models will need to include a middle atmosphere with fully resolved chemical and dynamical responses to solar variability, and they must also have adequate atmosphere-ocean couplings.

We are not yet sure what available proxies of past solar activity (specifically the ^{14}C and ^{10}Be cosmogenic isotopes) tell us about solar irradiance changes, even though these proxies enjoy widespread use in paleoclimate studies as indicators of solar irradiance variability. Dynamo-driven changes in solar magnetism affect solar irradiance and the heliosphere (that modulates cosmic rays) through different processes, and in different ways, related to the transport, evolution and heliospheric extension of solar magnetic fields. Quantitative studies are needed to characterize the respective pathways.

We do not know the fundamental causes of total and spectral irradiance variations, although they are clearly related to solar magnetism. Solar irradiance (both total and spectral) variability needs to be related quantitatively to the solar dynamo, and understanding improved of both magnetic and purported non-magnetic physical origins on multiple time scales. Without this physical underpinning, the ability to predict future and specify past irradiance variability will remain limited.

Stratospheric temperatures vary over solar cycle periods and are thought to be caused by solar radiative and particle modulation of the ozone layer. These solar cycle-related influences are more muted in the troposphere, but are still apparent there, and it appears that there may be a link between stratospheric and tropospheric changes. Models being used to address this problem have identified processes that closely couple solar forcing in the stratosphere and subsequent influences in the troposphere; however, the interactions are presently only crudely represented.

Objective: Identify and quantify the changes in Earth's near-surface temperature and other climate parameters attributable to solar variability from both direct and indirect solar energy forcings.

Priorities:

- Develop a robust observational and mechanistic description of climate change associated with solar variability.
- Incorporate candidate solar driver processes into available climate and coupled stratosphere/climate models.
- Clarify the interpretation of solar proxy data.
- Improve models of solar irradiance, including coupling to the solar dynamo, for long-term studies and more reliable long-term predictions.
- Quantify the influence of solar-driven stratospheric ozone variations on climate change.

2.3.2 Stratospheric ozone change

Societal Consequences: Solar-driven global and regional stratospheric ozone changes modify the surface flux of biologically-damaging ultraviolet radiation.

Problems and Needs: Stratospheric ozone variations during the 11-year solar activity cycle have been quantified to a certain extent from two decades of global space-based observations and the longer duration ground-based records. However, interference in this solar-based signal in the past 25 years caused by the decrease in ozone, resulting from the large increases in halogens in the atmosphere from industrial chlorine and bromine compounds and from major volcanic eruptions in 1982 and 1991, was significant in the lower stratosphere. The amount of chlorine and bromine in the stratosphere is projected to be relatively constant over the next 5-10 years and, barring major volcanic eruptions in the near future, it is likely that solar cycle-driven stratospheric ozone variations can be better quantified.

EUV radiation and the precipitation of charged particles (both electrons and protons) in the mesosphere and thermosphere produce nitric oxide, an ozone-controlling molecule. Nitric oxide can be transported to the stratosphere over a several-week period during polar night where it contributes solar-driven changes in the chemical loss of ozone. Most present models of the Earth's atmosphere are inadequate to address this problem since the models are not capable of properly representing the atmospheric processes from the troposphere to the thermosphere; however, some recent model developments have led to better methodologies for including all the relevant processes.

Objective: Identify and quantify the changes in ozone distribution attributable to variations in the solar output of electromagnetic radiation and energetic particles.

Priorities:

- Develop the ability to separate atmospheric processes, such as volcanic eruptions and man-made influences, from solar cycle-driven changes in stratospheric ozone.
- Quantify the effects of solar-driven changes in the thermosphere and mesosphere on the stratosphere.
- Incorporate effects of solar variability in coupled upper atmosphere/lower atmosphere models.

3.0 SPACE WEATHER AND SPACE CLIMATE

3.1 Introduction

Solar variability produces large changes in the charged particle and electromagnetic field environment of near-Earth space and the ionosphere in ways not yet understood. On a time scale of hours and days these changes in the Sun-Earth system are commonly referred to as "space weather." The overall variability of the Sun-Earth system on longer time scales is commonly referred to as "space climate", by analogy with lower atmosphere weather and climate. Effects associated with both space weather and space climate can seriously influence the performance and reliability of satellite and ground-based technologies as well as endanger human health and life. The National Space Weather Program (NSWP) (see Appendix 6.2.1) emerged in 1994 from the efforts of several U.S. government agencies to prepare the country to deal with technological vulnerabilities associated with the space environment. NASA's LWS program, and in particular its TR&T component, is an integral part of this interagency effort.

The origins of space weather and space climate lie within the Sun's interior where the solar magnetic field is generated. Variations in the solar magnetic field affect the total photon, plasma and energetic particle output from the Sun. Variations in those outputs, in turn, are directly responsible for changes that occur in the near-Earth space environment. The most rapid and dramatic changes in the solar output occur during solar flares and coronal mass ejections (CMEs). More gradual changes in the output occur on a variety of time scales. Perhaps the best-known long-term variations in the solar output experienced near Earth are those associated with the 27-day rotation period of the Sun and the 11-year solar activity cycle.

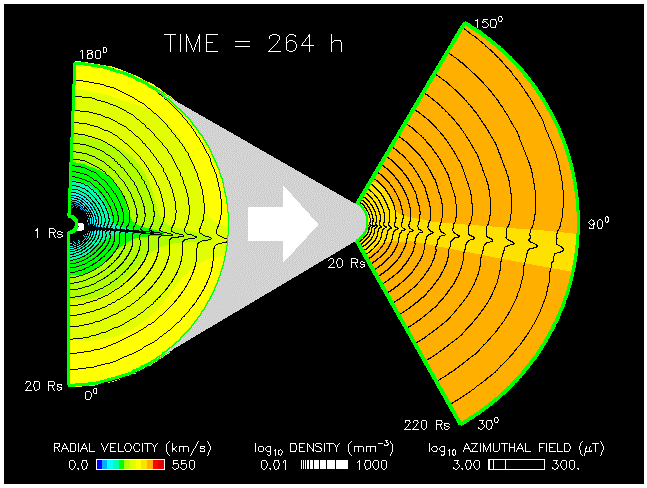


Figure 4. Coupled coronal/inner heliospheric and outer heliospheric calculations.

The solar coronal expansion, which is modulated by the solar magnetic field, produces the solar wind. Spatial variability in the expansion, when coupled with solar rotation, produces co-rotating solar wind disturbances, while the episodic CMEs produce transient solar wind disturbances. Solar wind disturbances often produce large geomagnetic storms when they interact with the Earth's magnetosphere. The largest changes in the Earth's radiation belts and in the ionosphere typically occur during geomagnetic storms and during large solar energetic particle (SEP) events produced by solar flares and by CME-driven shocks in the solar wind. However, since the solar wind and the embedded heliospheric magnetic field impinging on the magnetosphere are always variable to some degree, space weather conditions within the magnetosphere change continuously.

Earth's ionosphere is created by solar EUV radiation that ionizes neutral nitrogen and oxygen species in the upper atmosphere. Thus, changes in the solar radiative output associated with, for example, solar flares and the advance of the solar activity cycle directly affect the upper atmosphere and ionosphere. The magnetosphere and the ionosphere are also strongly coupled to one another, in the sense that the ionosphere directly affects the magnetosphere's interaction with the solar wind and most changes in the magnetosphere are manifested as enhanced electrical currents, auroral emissions, frictional heating, ionization and scintillation in the ionosphere and thermosphere. The ionosphere is also influenced by processes originating at lower altitudes, such as gravity waves and direct energy deposition from solar radiation and cosmic rays. In turn, changes in currents flowing in the ionosphere in the form of "electrojets" induce currents that flow within Earth's surface.

This brief description of space weather and space climate illustrates some of the complexity of the coupled Sun-Earth system as well as the variety of physical processes that must be understood in dealing with effects of solar variability. It is apparent that we cannot fully understand processes and effects in one region of the system without understanding the way the entire system is linked.

3.2 Hazards Associated with Space Weather and Space Climate

Space weather and space climate can have deleterious effects on a variety of technologies important to the nation. These include decreased lifetimes and degraded operational performance of space systems, damage to electrical power grids and associated power losses over large geographical areas, navigation errors experienced by users of the Global Positioning System and the Long-Range Navigation system, and degradation of high frequency (HF) and ultrahigh frequency (UHF) communications. Energetic particle radiation associated with space weather can also adversely affect astronaut health (particularly during extra-vehicle activities) and that of passengers and crews aboard high-altitude aircraft traveling in the Earth's polar regions.

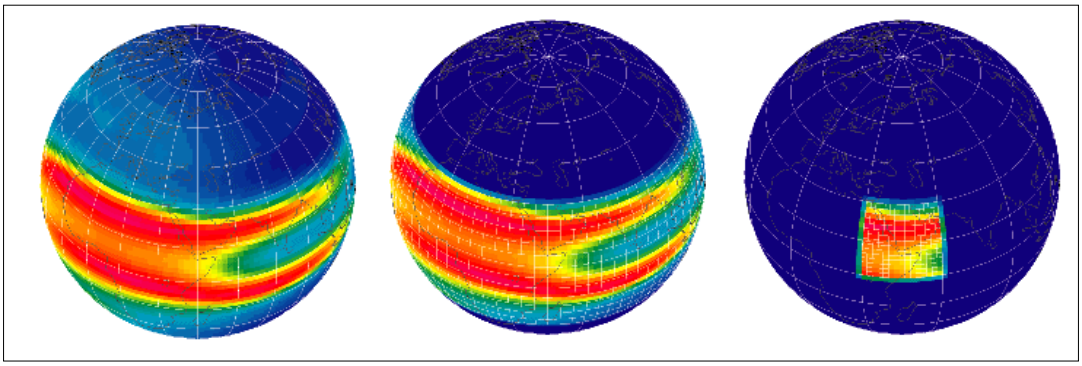


Figure 5. Assimilative modeling of the ionospheric electron density: Effects of resolution changes.

The following section describes near-term research priorities associated with hazards associated with space weather and space climate. In each subsection, the societal consequence of the hazard is described, and the problems and needs for addressing the hazard are outlined. Specific objectives relative to each hazard are then defined and the highest priority tasks required to reach these objectives are identified. Underlying all of these immediate priorities is a long-term priority to understand and model the various processes that link the Sun-Earth system and that are responsible for space weather and space climate.

3.3 Research Priorities

3.3.1 Background ionosphere

Societal Consequences: Variations in the background ionosphere on spatial scales >100 km and temporal scales >1 hour adversely affect communication, navigation, geolocation, surveillance and radar systems.

Problems and Needs: The coupled ionosphere-thermosphere system and its variations in response to changing solar EUV and X-ray irradiance on a variety of time scales are not yet sufficiently well understood to enable reliable specification and prediction. Also, the combined effects of composition, winds and electric fields on the low and middle latitude F-region are not predicted very well by existing first-principles models for either quiet or storm times. Of particular importance is the effect on the ionosphere of variations in low and mid-latitude electric fields due to upper atmosphere dynamo action and electric field penetration from high latitudes. Presently, we are not able to model the coupling processes with sufficient accuracy to describe the prompt penetration of electric fields imposed by the solar wind to low latitudes or to model how winds and the neutral atmosphere modify the ambient ionosphere.

Objective: Predict the effects of space weather on the global behavior of ionospheric density in the altitude range from 100 to 1000 km.

Priorities:

- Develop a dynamic thermosphere-ionosphere model.
- Develop the capability to specify low and mid-latitude electric fields.

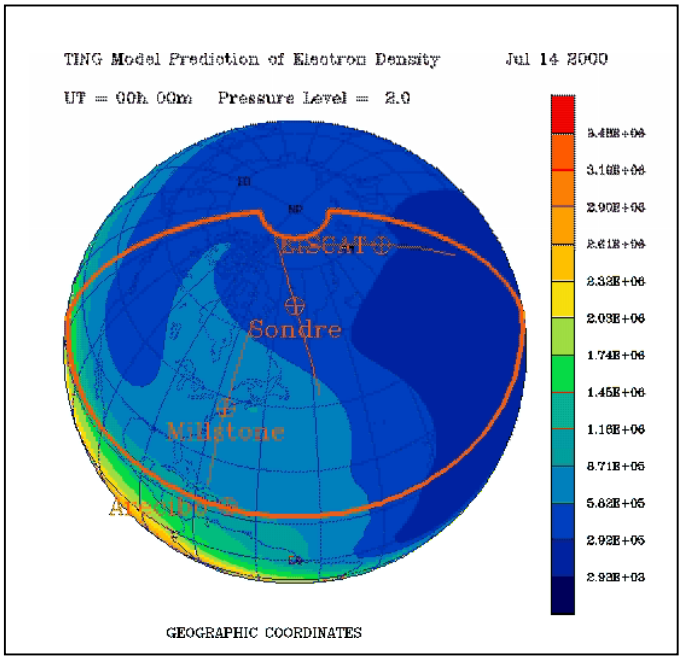


Figure 6. Model prediction of ionospheric electron density.

3.3.2 Ionospheric scintillations

Societal Consequences: Scintillations caused by ionospheric irregularities on spatial scales <100 km progressively degrade and disable navigation, communication, surveillance and radar systems.

Problems and Needs: Plasma instabilities in the ionosphere at both high and low latitudes generate irregularities that affect radio wave transmissions, causing signal degradation known as ionospheric scintillation. Scintillation occurs more frequently and extends over a larger range of heights in the ionosphere during times of high solar activity and is particularly severe at low latitudes, where the irregularities have a large spatial extent. Numerical simulations of ionospheric irregularities are still in their infancy, in part due to lack of observations of the main drivers of the instability. We need to understand the factors that trigger and suppress instability, the factors responsible for the longitudinal variations in scintillation activity, and the way the instability evolves in time and space. One of the most urgent requirements is to be able to predict several hours in advance which geographical regions will be affected by scintillation. Thus, we need to understand the factors that control the growth-rate of the instability, and determine how ionospheric plasma bubbles evolve. Models of the electrodynamics at low and mid latitudes are needed to elucidate the complex electrodynamic interactions between dynamo electric field, penetration electric fields, neutral densities, and winds.

Objective: Quantify the influence of space weather on the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.

Priorities:

- Develop accurate onset and evolution models of plasma instabilities in the ionosphere.
- Develop and test models of electrodynamics at low and mid latitudes.

3.3.3 Density and composition of the neutral thermosphere

Societal Consequences: Changes in the density and composition of the neutral atmosphere create variable satellite drag, adversely affecting our ability to identify and track objects in space and to predict their re-entry into the atmosphere.

Problems and Needs: In recent years, models of the coupled thermosphere-ionosphere system have been developed that identify the major contributors to the aeronomy of the upper atmosphere. These models make predictions of the climatology of the ionosphere-thermosphere system by tuning a large number of input parameters. However, there are still major uncertainties about parameterizations used in the models, and many of the model inputs. As a result, the models are generally unable to simulate accurately the ionosphere-thermosphere characteristics even on a time scale of days without a great deal of tuning. Very little work has been done to validate the global models with large ionosphere-thermosphere data sets. Work in this area will lead to improvements in the first-principles models, and make them suitable for eventual use in modeling the weather and climate of the ionosphere and thermosphere. Some of the uncertainty in the global first-principles models results from uncertainty in the inputs of upward propagating waves and tides, solar fluxes at a range of wavelengths, and high-latitude particle precipitation and electric fields. Measurements of the solar fluxes have started to become available, but the upward propagating tides and waves and the high-latitude inputs have large uncertainties. Research is needed to refine our understanding of these ionosphere-thermosphere drivers and their effects.

Empirical ionosphere-thermosphere models provide approximate values for various parameters needed by many researchers for operational systems and for input into other models. However, present models have limited accuracy, reflecting the sparseness of the data sets used in their construction. New data are available that could provide new models or improvements to the existing models. Particularly lacking are global wind specifications, which are important for driving changes in the thermosphere and ionosphere. The existing wind climatologies have proved to be inaccurate.

Objective 1: Determine the effects of long and short-term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe these effects with accuracy better than 5%.

Objective 2: Understand and predict satellite drag variations during geomagnetic storms and during the solar activity cycle.

Priorities:

- Develop accurate empirical neutral wind models.
- Develop more advanced thermosphere density and composition models.

3.3.4 Geomagnetically-induced currents

Societal Consequences: Geomagnetically-induced currents in power lines and pipe lines disrupt power systems and contribute to pipeline erosion.

Problems and Needs: Our understanding of geomagnetically-induced currents (GIC) in power lines and pipe lines is limited, but it appears that the local dynamics of the high-latitude electrojets flowing in the ionosphere plays a dominant role. In particular, the rate of change of the electrojets is of the greatest importance. There are several aspects to the rate of change. First, general expansion of the open-field polar cap during geomagnetic storms can cause the electrojets to move equatorward rapidly. Second, localized enhancements in either the electric field or the ionospheric conductivity, or both, can produce rapid changes in the electrojets.

In order to mitigate the damage that GIC can do to power transmission systems, power companies need a minimum of 30 minutes to an hour of advance warning. In general, an ability to predict and characterize geomagnetic storms is needed to provide such advance warning but, because of the highly localized nature of GIC events, highly detailed modeling of the ionosphere is also needed (see

also 3.3.1). Accurate models of particle precipitation on scales of the order of 100 km are needed to understand the dynamics of the ionospheric conductivity, as are accurate models of the ionospheric electric field on small spatial scales.

Objective: Develop the capability to forecast induced currents produced by changes in ionospheric current systems driven by geomagnetic activity.

Priorities:

- Create a high-latitude conductance model with ~100 km spatial scales and ~ 1 minute temporal scales, including effects of solar irradiance variability and particle precipitation.
- Develop high-latitude electric field models with resolutions of ~100 km and ~ 1 minute.

3.3.5 Energetic particle environment in the magnetosphere

Societal Consequences: Energetic particles in the magnetosphere adversely affect the performance and lifetime of space systems operating there, and can be a health threat for astronauts.

Problems and Needs: Current specification models for the radiation environment within the magnetosphere are based upon data that are decades old and out of date. New data from more recent science missions can and should be incorporated into improved specification models for the magnetosphere that also take advantage of recent progress in understanding particle acceleration and loss processes. Next-generation, time-dependent radiation belt specification models can be parameterized by solar activity, magnetic activity and solar wind conditions, and can use data assimilation to improve their accuracy. Similarly, new capabilities for simulating inner magnetospheric dynamics integrated within large-scale models of the solar wind-magnetosphere interaction allow, for the first time, realistic physics-based models of particle acceleration and loss in the radiation belts. The near-term development of more capable specification and physics-based models that include real-time data assimilation will contribute powerful new data analysis technology in time to support the LWS Radiation Belt Probe mission. The largest changes in the magnetospheric radiation environment occur during geomagnetic storms and substorms. Our improved understanding of how such events are triggered by disturbances in the solar wind and the general availability of upstream solar wind data indicate that the time is ripe to model the magnetospheric response to specific solar wind conditions.

Objective 1: Develop accurate specification models of the Earth's radiation environment from tens of eV to GeV energies on timescales from seconds to decades.

Objective 2: Create scientific understanding needed to model the physical processes responsible for the acceleration, transport and loss of radiation belt particles throughout the magnetosphere.

Priorities:

- Create accurate empirical radiation-belt specification models.
- Create new understanding and physics-based models of particle injection, acceleration, transport and loss that include the solar wind-magnetosphere interaction.
- Create next-generation magnetospheric electric and magnetic field models that include the inner magnetosphere.

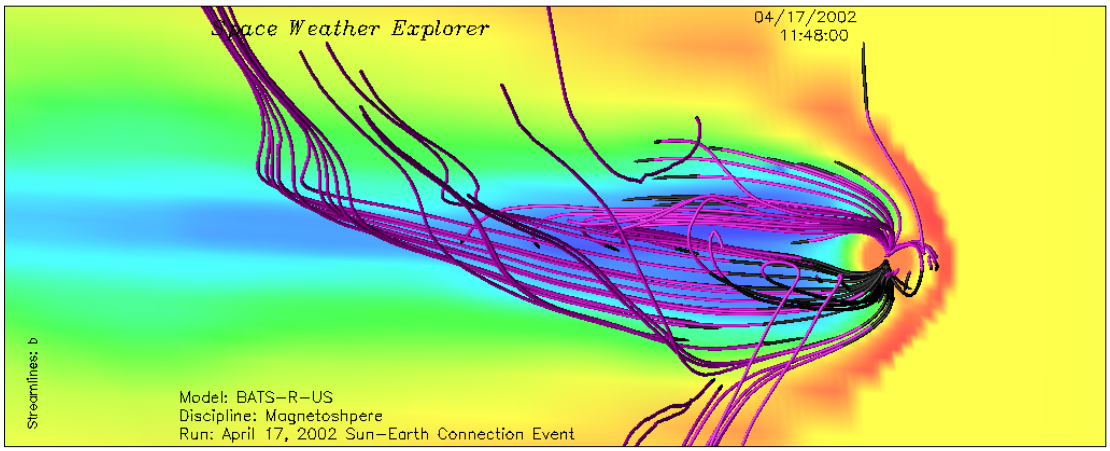


Figure 7. MHD model of the Earth's magnetosphere during the April 17, 2002 events.

3.3.6 Radiation associated with explosive events on the Sun

Societal Consequences: Solar energetic particles are a radiation hazard for astronauts and for crews and passengers on high-flying aircraft at polar latitudes, adversely affect radio communication at high latitudes, and contribute to the degradation of spacecraft systems.

Problems and Needs: Our present ability to predict SEP fluxes in the vicinity of Earth's orbit is limited. Accurate prediction of SEP fluxes at Earth rests on the development of several capabilities. These include a detailed understanding of particle acceleration at CME-driven shocks and subsequent transport out to Earth orbit, understanding and models of the propagation of CME-driven shocks through the structured solar wind, specification of the structure of the ambient solar wind plasma and magnetic field in the ecliptic plane out to 1 astronomical unit, and specification of the mass, momentum and energy content of CMEs. To predict arrival times with even moderate lead-time (a few hours) requires forecasting CME events prior to their eruption.

Objective: Develop the capability to forecast and predict the intensity of energetic particles accelerated by CME-driven shock disturbances in the solar wind.

Priorities:

- Understand and model the shock acceleration and heliospheric transport of energetic particles.
- Create models of CME-driven shock disturbances that include realistic CME and ambient solar wind initial conditions.
- Develop and progressively improve the specification of the ambient coronal and solar wind plasma and magnetic field.

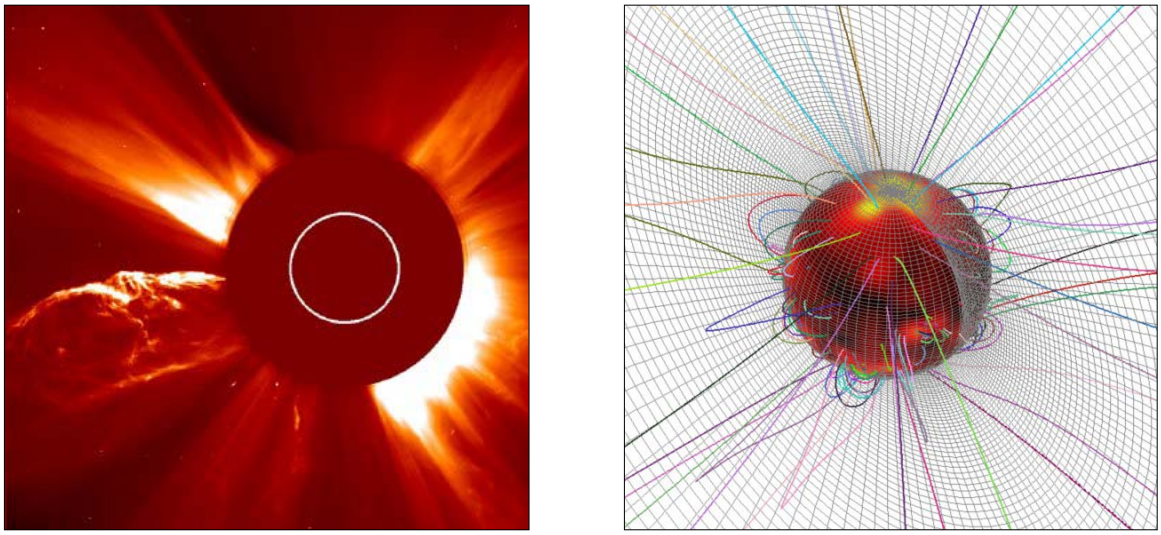


Figure 8. Left – LASCO image of a CME in the solar corona. Right – global MHD model of the solar corona.

4.0 THE TR&T MISSION CONCEPT

4.1 Overview of TR&T Mission

The LWS Program confronts two great challenges: 1) To deliver scientific understanding that integrates across the widely disparate Sun-Earth physical domains; and 2) To demonstrate how this knowledge can be used to benefit society. The role of the LWS spacecraft missions is to obtain those measurements of the Sun-Earth system that are essential for obtaining the desired understanding. The role of the TR&T program is to integrate scientific output, data and models from LWS and other sources to generate a system-wide picture of Sun-Earth connection science. In addition, NASA Headquarters has decided that efforts directed at improving measurement capabilities for future LWS missions should also be a part of the TR&T program. A high level of organization and planning is required for a successful TR&T program. In the following we refer to our design for TR&T as the "TR&T Mission."

The specific strategies for achieving a broad understanding targeted at societal impacts are embodied in the research priorities described in Sections 2 and 3. For some of these research priorities, improvements in specification through exploitation of existing and emerging databases can provide rapid progress and impact (e.g., in the case of radiation belts and the ionosphere and thermosphere). The near-term needs in other problem areas rest on model development and model improvements based on higher densities of measurements in space and time (e.g., ionospheric scintillation, ionospheric impacts of spectral irradiance variations in flares). Still others will be addressed by the analysis of data sets returned from forthcoming LWS missions. However, forecasts and predictive capabilities require a systems approach with cross-disciplinary modeling and should be a continuing long-term focus. In order to achieve this systems approach, physical processes must ultimately be followed from Sun to Earth, and all important links and feedbacks must be identified through data analysis, theory and modeling. Strategies unique to Sun-climate/ozone research place another set of constraints on the program. Long-term variations relevant to climate/ozone change issues require analysis of extensive historical databases, and numerical simulations of solar variability over long time scales. In addition, identification of the specific pathways by which the signatures of solar variability in the upper/middle atmosphere are currently coupled to tropospheric responses is a necessary next step to progress in understanding linkages between solar variability and climate/ozone

change. New knowledge of these linkages must be embedded in existing community climate/ozone models extended to include the coupling with the stratosphere, mesosphere and thermosphere. This new knowledge must also influence and refocus studies of solar variability and climate change in historical records.

Given the scope and magnitude of the priority targets, the SDT concludes that the TR&T mission needs to include a variety of science methodologies (e.g., theory, modeling, data analysis, and technology development) and a range of types of investigations (e.g., single institution projects, large multi-institution programs). Since the programmatic targets span the Sun-Earth system, the TR&T mission must be able to draw on the collective talents and creativity of the Sun-Earth science community. Moreover, the mission must be able to evolve as our understanding and capabilities advance during the decade-long duration of LWS. Therefore, the SDT recommends that the fundamental components of the TR&T mission be projects that are competed openly on a regular basis. Furthermore, the SDT recommends that these projects be arranged into two basic structural elements: *targeted investigations* and *strategic capabilities*. Both structural elements share the defining features of targeted prioritization, schedule and deliverables. *Targeted investigations* are analogous to science investigations supported by the NASA-SEC basic science R&A programs. The purpose of the *targeted investigations* element is to promote creative new approaches to the priority targets by allowing for proposals that are unrestricted in approach or scope. The SDT expects that most *targeted investigations* will be focused on advancing science understanding, but they could instead be focused on applications. The *strategic capabilities*, on the other hand, will largely be science tool and/or prototype operational model development efforts that are required by the TR&T mission. We describe *strategic capabilities* more fully in Section 4.5.

4.2 Target Prioritization

The TR&T Program must have the flexibility to take advantage of the best ideas and technical innovations; consequently, all proposals that address the general LWS goals should be considered for support. On the other hand, TR&T must be a **targeted** program. The main reason is that TR&T must deliver enabling science; it must demonstrate science advances that can have an impact on societal needs. Another important reason for a targeted program is that, at any given time, some areas of research are more likely to yield near-term useful results as, for example, when a flight mission begins to deliver new observations. Directing resources to targeted areas will advance LWS goals most effectively. The targets will evolve with the program and should be selected by the TR&T Steering Committee, the oversight board described in Section 5 below. Proposals that are judged equal in science content and societal relevance should be selected on the basis of how well they address a *prioritized target*.

4.3 Schedules and Deliverables

LWS calls for science with the potential of enabling practical application in the Sun-Earth system domain. This requirement of relevance mandates that every TR&T project define its deliverables and their potential relevance to societal needs, as well as the timetable for generating products. These deliverables should not be expected to be operational tools. Nor should it be expected they must all be delivered or linked to a modeling center or data center (except in the case of *strategic capabilities* for which this should be a requirement). In the case of *targeted investigations* the deliverables can be data analysis results, procedures or empirical models made available through publication in the open literature or, if appropriate, analysis tools provided for the LWS missions. The perceived relevance and value of the proposed deliverables should be given equal weight to the proposed science by peer review panels. A project that does not adequately address the LWS mandate of relevance should not

be suitable for the TR&T program. The success of the TR&T program will be judged by the quality of the proposed deliverables, by the success of the selected projects in delivering as promised and on schedule, and by the impact the deliverables have on scientific understanding, end users and government policy.

4.4 Cross-Disciplinary Research

One of the great challenges for LWS is to achieve the "systems" science required for enhancing our understanding and capabilities in predicting Sun-climate/ozone change and space weather, phenomena that span the whole Sun-Earth domain over many time scales. For example, a first principles-based predictive capability for disturbances due to a solar eruptive event will clearly involve understanding the complete Sun-Earth physical chain. But achieving the necessary systems understanding poses major difficulties. It requires developing an understanding of coupling among different physical domains, such as the photosphere and corona, the corona and solar wind, the corona and ionosphere and thermosphere, or the magnetosphere and the ionosphere -- domains that each involve different underlying physics. For example, the corona is a magnetically dominated, collisional plasma, whereas the solar wind is momentum-dominated and essentially collisionless. Similarly, the magnetosphere is a nearly fully ionized, highly conductive plasma, whereas the ionosphere is only partially ionized and resistive. Modeling the coupling of such disparate domains is one of the most difficult problems in all of physics. But, these are exactly the type of problems that must be solved in order for LWS to succeed.

One factor that has impeded progress in cross-disciplinary research is that the science community and, consequently, traditional NASA R&A programs, have always been structured according to discipline boundaries (e.g., solar, heliosphere, magnetosphere, ionosphere, thermosphere, atmospheric chemistry, and climate). Thus, the types of cross-disciplinary projects that LWS needs most are the ones least likely to be proposed to the traditional NASA-SEC basic science R&A programs, and are the ones least likely to be supported there.

It is vital, therefore, that the TR&T program foster and support cross-disciplinary activities by giving preference to projects that cut across discipline boundaries and involve domain-coupling problems. Such projects should be deemed to have high relevance, because they address a critical need of LWS. Furthermore, the TR&T program should encourage activities that train cross-disciplinary researchers. Workshops and summer schools are possible avenues for addressing these development needs and for fostering cross-disciplinary research. Note, however, that proposals to develop such cross-disciplinary infrastructure should still be required to outline the anticipated outcome of the proposed activities and to describe how success will be measured.

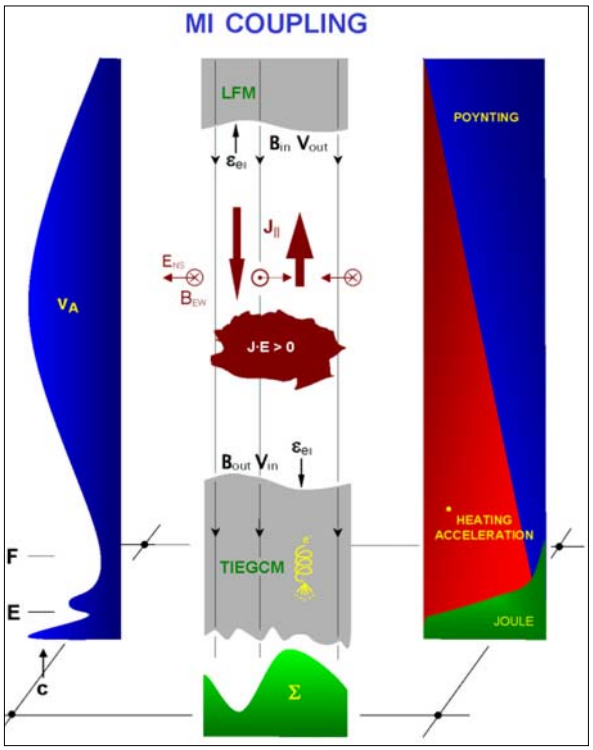


Figure 9. Elements of magnetosphere-ionosphere coupling.

4.5 Strategic Capabilities

A primary goal of the LWS Program should be the development of first-principles-based predictive and specification models for the coupled Sun-Earth system, similar in spirit to the first-principles models for the lower terrestrial atmosphere, which couple to the oceans and polar icecaps. Such models are essential for making progress on some of the science priorities identified in Sections 2 and 3 and to assist in the interpretation and linking together of the data that will be produced by the LWS missions, other NASA-SEC missions, and ground-based facilities. Models serve multiple purposes. They act as tools for science investigations, as prototypes and test beds for first-principles-based prediction and specification capabilities, as frameworks for linking disparate data sets at vantage points throughout the Sun-Earth system, and as strategic planning aids for testing new mission concepts. Consider, for example, the suite of atmospheric models developed by the National Center for Atmospheric Research. These readily available models are at the heart of many of the basic science investigations presently being performed in atmospheric sciences, and some are also used regularly for atmospheric specification. Furthermore, one or more of them could serve as the atmosphere component of a Sun-to-Earth linked model chain. The development of such models for all the components of the Sun-to-Earth system and the larger efforts that combine the components into a global system view would clearly be of enormous benefit to LWS science.

To begin the process of developing and integrating components of the Sun-Earth chain, the SDT has identified these components and their integration as *strategic capabilities* that are critical for the TR&T program. Illustrative examples include a dynamic thermosphere-ionosphere model (section 3.3.1), a physics-based model of particle injection, acceleration, transport and loss in the magnetosphere that includes the solar wind-magnetosphere interaction (section 3.3.4), or a model of the ambient corona and solar wind plasma and magnetic field based on vector magnetic field measurements in the photosphere (section 3.3.5). Ideally these efforts will leverage existing

modeling resources, but will also likely require significant new code development and possibly multi-institutional collaborations. Since the primary function of such code development is to provide a tool for science and a prototype operational tool (similar to an instrument development effort rather than a science investigation), the TR&T Definition Team recommends that proposals for *strategic capabilities* should be competed separately from the *targeted investigations* efforts. The defining characteristics of a successful proposal to provide a *strategic capability* should include, but need not necessarily be limited to, the following:

1) The project delivers a model that is deemed by the review panel to be essential for making progress toward the ultimate goal of forecasting and specifying the coupled Sun-Earth system.
2) The model can serve as a prototype for operational capability; it must use actual data as input and produce useful output.
3) The project delivers a tool that is deemed by the review panel to have broad, cross-disciplinary science applicability. The size of the likely user base for the proposed tool should be a major factor in its selection.
4) The project provides easy access to the model, either directly by the developers or through a modeling center. In the case of software, the source code and documentation should be required to be delivered to one of the modeling centers utilized by LWS.

It should be emphasized that the characteristics above do not mandate proposals focused only on the development of large-scale, first-principles models. The SDT specifically identifies the components of such a Sun-to-Earth model as *strategic capabilities*, but if proposers have ideas for tools that are equally compelling, they should be encouraged to submit them to the *strategic capabilities* line. It may be, for example, that an empirical model might qualify as a *strategic capability*.

Priorities for *strategic capabilities* proposals should be set by the TR&T Steering Committee (see Section 5.1), based on the overall LWS program goals and research priorities discussed in Sections 2 and 3 of this report. The peer review panel should select, based on the submitted proposals, those *strategic capabilities* that are most ready for immediate development and are most important to the LWS program at that time.

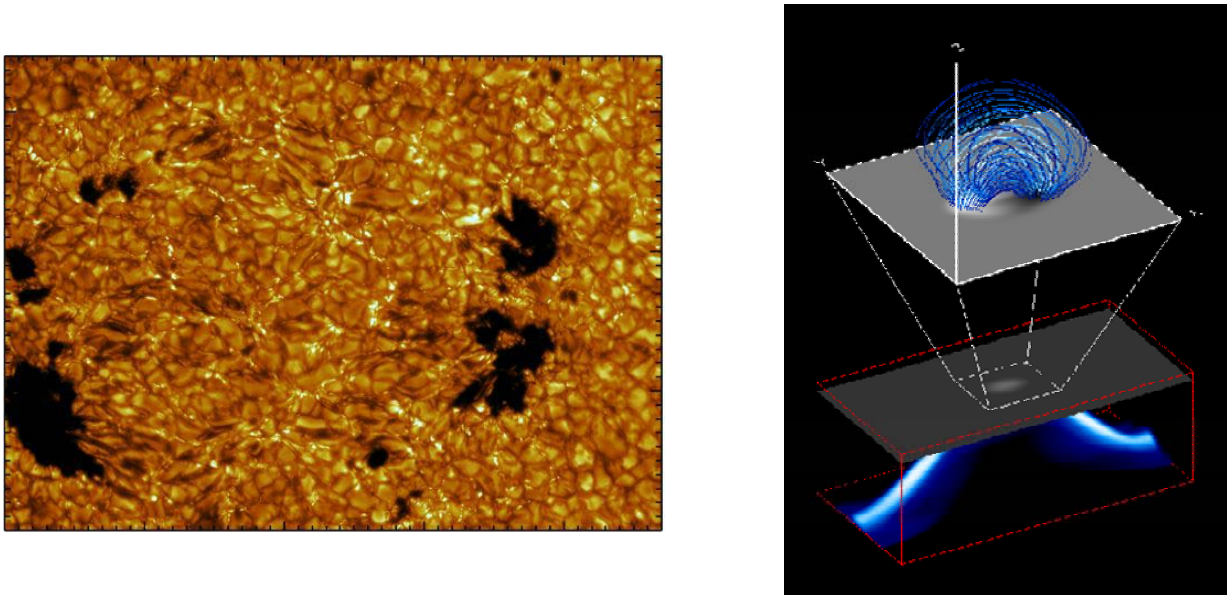


Figure 10. Left – high resolution image of the photospheric granulation network. Right – coupled model of the emergence of magnetic flux into the corona.

5.0 IMPLEMENTATION PLAN

5.1 Introduction

The TR&T mission has a number of goals that are central to the success of LWS. Among these goals are developing new scientific understanding, developing accurate empirical and physics-based models, developing data analysis tools, ensuring easy access to models and data, supporting research that crosses traditional discipline boundaries, and facilitating the transition of research products to users of space weather, space climate and climate/ozone information. As a consequence of the interdisciplinary nature of this program and the need to track progress in targeted areas, management and infrastructure issues must be carefully considered and new procedures for accountability established.

A significant factor for LWS is the modeling and data infrastructure. The SDT assumes that the overall NASA-SEC program will support the basic computing infrastructure needed for managing both data and modeling efforts for TR&T. In particular, the SDT assumes that modeling services, such as provided by the Community Coordinated Modeling Center (CCMC), will be separately funded outside of the TR&T program and will aid in archiving and facilitating some of the LWS modeling efforts. In addition, the SDT assumes that programs such as the Virtual Solar Observatory and its relatives within NASA-SEC will be supported separately so that finding, extracting and using LWS-related data will be relatively transparent to users. However, if TR&T funds are used for direct support of modeling and data facilities, an open competition should be held to select the best proposals for fulfilling these functions. Moreover, TR&T should support data environment proposals of direct and immediate benefit to the program itself. Examples might include: 1) Developing integrated data bases from disparate sources (e.g., a long-term data base of solar irradiance measurements from different sources); 2) Developing useful empirical models (e.g., for the radiation belt or auroral oval as a function of solar wind conditions, or for upper atmosphere composition and winds); 3) Developing and testing relevant data analysis tools (e.g., inversion techniques for helioseismology), 4) Developing visualization tools (e.g., for solar wind structure or radiation belt

environment); 5) Developing tools that enable the interactive selection of relevant data (e.g., by depicting location or setting thresholds); or 6) Developing new techniques for assimilating data into predictive models (e.g., for the ionosphere).

In the following sections we discuss specifics of our proposed implementation plan for TR&T.

5.2 Program Coordination and Oversight

NASA Headquarters (HQ) is the issuer of TR&T Announcements of Opportunity (AOs), assembles review panels, decides on programs to fund, and decides on appropriate funding levels. Both a TR&T Project Scientist and a TR&T Steering Committee (TSC) should assist NASA HQ in these tasks.

The TSC should include representatives from both the science and the application communities with overall membership rotating on staggered terms. It should be established as a sub-group of the LWS Missions Operations Working Group (MOWG) and have the responsibility to review TR&T progress, to review and change TR&T priorities as new knowledge becomes available or national needs change, and to recommend to NASA HQ priorities for future TR&T AOs. These functions should be performed in cooperation with the Project Scientist.

The TR&T project scientists should have as his/her responsibilities the representation of the program to NASA HQ and the LWS MOWG, the support of the activities of the TSC, the tracking of knowledge and capability growth within the TR&T program, and the determination of compliance with metrics, milestones, and deliverables of individual TR&T-funded projects. The TR&T Project Scientist should establish a special web site with up-to-date information on TR&T-supported research and development and should collect this information in direct support of NASA HQ, the LWS MOWG and the TSC.

5.3 Support Mechanisms

The SDT recommends that TR&T be implemented as a series of targeted research projects proposed in response to AOs. The announcements should indicate priorities for both *targeted investigations* for the upcoming funding cycle and *strategic capabilities* deemed essential to the success of the LWS program. The specific areas of emphasis for funding should evolve as the program progresses.

All parts of the TR&T program should be openly competed through the NASA peer-review process as much as possible. Open competition is the bedrock of all NASA research and technology programs, because it has proven to be the most effective mechanism for ensuring the best investment of resources. Open and regular competition is especially critical to the TR&T program, which requires flexibility and a continuous influx of new personnel, ideas and technologies as the LWS program evolves.

Proposal review panels should be predominantly Sun-Earth system scientists, but should also include representatives knowledgeable about the nation's needs in space weather and climate/ozone research. Proposals should be ranked on the basis of scientific merit, perceived value to the TR&T mission and its targeted priorities, the description of a credible set of deliverables, milestones and success metrics, and the track record of the proposers.

Due to the nature of the TR&T program, which invites proposals for *targeted investigations* and *strategic capabilities*, funding mechanisms beyond the normal grant proposals must be considered. While grants remain the tool of choice for smaller investigations, larger proposed activities often involve deliverables or products, similar to the delivery of a space science instrument for an LWS

flight mission. This is particularly applicable to proposals for development of *strategic capabilities*. Serious consideration should be given to funding *strategic capability* proposals on time cycles longer than the nominal three years and for staggering the start of these efforts to help ensure scientific continuity within the TR&T program.

There are two funding mechanisms for programs with specific milestones and deliverables. First, a Cooperative Agreement (CA) establishes a process by which funding in the following year is contingent upon completion of pre-defined milestones in the prior year. These milestones may consist of the demonstrated establishment of a certain capability, or the delivery of a product. The second mechanism involves the creation of contracts between NASA and the proposing entity. These mechanisms are particularly suitable for *strategic capabilities*, where the nature and scope of the product are largely known beforehand or set by NASA HQ based on advice from the TSC.

5.4 Accountability

The LWS TR&T program supports a variety of activities, each of which will require specific metrics and milestones to ensure that 1) progress is being made in each area, and 2) proposed activities address goals relevant to LWS. In this section we provide a recommended outline for the metrics and milestones that could be applied in each of the following areas: scientific understanding, data availability, data environment, model validation, model availability, instrument development and synergistic activities such as workshops and summer schools. The SDT recommends that the Project Scientist and the TSC review these metrics and milestones at least annually, and that the specific targets of each year's annual AO be structured to reflect the changing needs required for balance throughout the program. The measures of progress of this program must be publicly available, both to demonstrate the level of success of the program and to motivate effort in areas that are poorly understood.

Scientific Understanding

Progress in scientific understanding ultimately will be measured by reductions in the uncertainty of our specification and prediction of key parameters of Sun-climate/ozone relations and space weather. A brief section outlining the key understanding that will be targeted and the metrics that will be used to evaluate the results should be required in all TR&T proposals targeting increased scientific understanding. Proposed investigations should be evaluated in part on the perceived value of the suggested metrics. In projects where models are developed, investigations should be encouraged to demonstrate increased scientific understanding through quantitative comparison of specifications and/or predictions with measured quantities, using measured quantities as inputs. Progress reports submitted by the investigators should include the results of these quantitative tests, where appropriate.

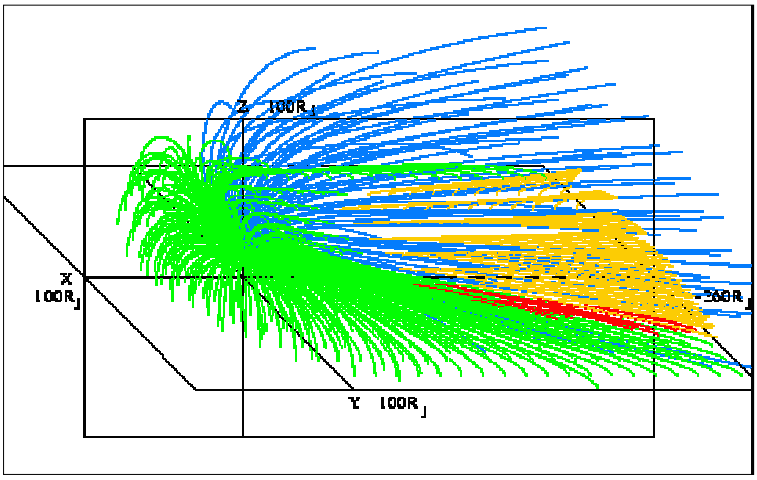


Figure 11. Magnetospheric magnetic field structure from global MHD models: Topologies are indicated by color.

Data Availability

The success of the TR&T program will depend critically on the efficient access to data from throughout the Sun-Earth system, including NASA and non-NASA sources. These data will be essential for scientific data analysis, empirical model development, physics-based model development, data assimilation, and the driving and verification of models. It will require numerous interagency and international partnerships, as well as focused internal NASA effort, to ensure ready access to large and diverse data sets. At regular intervals, the TSC, in conjunction with the TR&T project office, should determine the priority of non-NASA data sources required for the success of the TR&T program. The TR&T project office should maintain a catalog of available data sources and statistics on data usage.

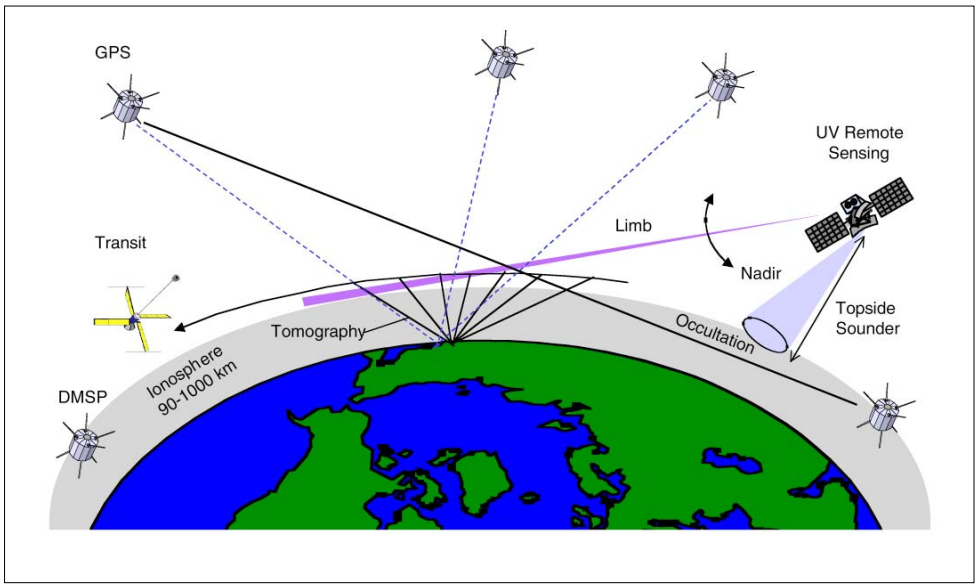


Figure 12. Candidate data sources for assimilative ionospheric modeling.

Data Environment

Basic data analysis tools that improve the overall LWS data environment are one possible result of TR&T-supported research. It seems likely that many such products will also be generated within the context of ordinary research projects in the *targeted investigations* category. These products should be considered deliverables and spelled out explicitly in proposals, where appropriate. The SDT recommends that the LWS project should establish WWW pages that provide links to the tools returned by the program. In some cases, the project may find it desirable to provide resources to analyze data remotely using these tools.

Model Validation

Models are developed for a variety of reasons. For example, models can provide predictive capabilities, scientific insight, or boundary condition for another model. For models developed under the aegis of TR&T, two categories of validation are recommended: scientific validation and metrics studies. All the models should be subject to scientific validation, in which the developer or an independent scientist demonstrates that the model produces physically realistic outputs. Whenever possible, data assimilation should be included and the model output should be compared with actual measurements.

Metrics studies are an objective way of comparing model capabilities, or tracking the improvement of a single model over time. In metrics studies, a model is subjected to a specified set of initial conditions and compared with measured values. For those models designed for transition to operational users, an uninvolved party should perform the metrics studies.

Some of the larger modeling groups participating in Sun-climate/ozone research will be expected to participate in model-model and model-measurement inter-comparisons, as appropriate. Such inter-comparisons will test the radiation, transport, chemistry, and certain physical mechanisms used in the global models. These inter-comparisons will include modeling exercises to examine the justification of the use of particular models and applied methodologies to study particular solar influences.

Model Availability

In order to maximize the usefulness of TR&T-developed models throughout the scientific and application communities, the models must be broadly available and readily usable. Efficient access to robust, documented models will increase the number of scientific investigations that use them, allow comprehensive testing, and foster cross-disciplinary activities involving model coupling. TR&T proposals submitted for model development should be required to describe the expected model outputs and required inputs, and specify the mechanism by which the model will be made publicly available. The latter might be satisfied by performing model runs as requested or by making the model available at a modeling center. Models intended for execution by non-experts should have sufficient documentation and validation to enable users of the model to determine valid ranges of input parameters, valid ranges of output parameters, and some measure of accuracy based on comparison with historical data. A key measure of success of the TR&T program will be the availability and broad use of such models with demonstrated reduction over time in the uncertainty of key derived physical parameters.

Instrument Development

Development grants should be awarded for promising hardware efforts directed at improving measurement capabilities for future LWS missions. These could include smaller or cheaper versions of existing instrumentation, or novel instrumentation for new measurements directly applicable to

LWS goals. TR&T proposals submitted for instrument development should specify the design goals and intended application of the instrumentation as well as milestones and deliverables for the project.

Synergistic Activities: Workshops and Summer Schools

The integration of scientific understanding across disciplines to achieve a system-view understanding of the Sun-Earth system is a "mission-critical" element of the TR&T program. Without this understanding, it will not be possible to develop a physics-based capability to extend significantly the lead-time on space weather forecasts or to predict long-term solar variability and its connection to climate/ozone change. In response to this need, the SDT recommends that there be a program element that supports venues for collaborative research activities such as workshops and summer schools. New knowledge generated by these synergistic activities should be made available to the scientific community either through archived system-wide data sets, coordinated publications or model products. Proposals to organize these activities should be required to include a brief section on metrics and milestones that outline the anticipated outcomes and how they will be measured. The TR&T project should maintain a public record of the proposed goals and actual accomplishments.

5.5 Connection to the LWS Flight Program

LWS flight missions will provide unprecedented new data sets and new insights into the physical mechanisms that underlie the Sun-Earth connected system. Success of LWS requires a close integration of LWS flight missions with the TR&T mission component. In particular, LWS missions will benefit from specific models that permit the integration or further the interpretation of their measurements.

While the synergy between TR&T goals and LWS mission goals is natural, specific measures need to be taken to ensure a continuous, tight integration between LWS missions and TR&T. Specifically, the SDT recommends that LWS mission science working teams include representatives from TR&T, both from PI activities as well as from the TR&T project scientist staff. Furthermore, LWS mission representatives should become part of TR&T science working groups. The LWS MOWG will have as one of its functions to provide a strong integration of all activities across the LWS program. In this role, the LWS MOWG should pay particular attention to the interfaces between flight missions and the TR&T mission.

5.6 LWS Modeling and Data Center Functions

Models and analysis tools developed through activities supported by TR&T follow an "open model/open tool policy," analogous to the open data policy applying to LWS mission data. This open policy requires that model and data analysis results developed by LWS be accessible to the entire scientific community and to the agencies and industries that produce space-related products and provide space weather services in the United States, as well as to international organizations that provide assessments of anthropogenic impacts on climate and ozone. For space weather applications, a capability is needed to foster the transition of selected models with potential application utility to operational space weather forecasting centers.

Depending on the nature of the model or analysis tool, access via a modeling or data center could occur in one of two ways. First, the model or tool could be retrieved from a repository as source code with documentation. This access will, in most cases, be appropriate for relatively simple tools and models. Second, users could request model and analysis services from the modeling or data center and receive results after execution completes. Ideally, both submission and result access would be

provided by simple-to-use, standardized interfaces to optimize utility for scientists and others who are not familiar with the intricacies of each service they desire to use.

For TR&T, the following modeling and data center functions are essential:

1. Permanent archive for LWS data, model drivers and output, as well as software developed under TR&T.
2. Open access to LWS and other NASA-SEC mission data and tools.
3. Access to critical, non-NASA data sets.
4. Performance of runs on demand of models deemed critical by the TSC.
5. A mechanism to transition, where appropriate, models and tools developed under the TR&T program to users.
6. Model and analysis tool performance evaluation and testing. Like mission data, models and tools developed under the TR&T program should be verified through an appropriate method of science-based validation. In the case of a model destined for transition to operations, the evaluation and testing must provide an independent, disinterested assessment of model performance according to metrics.

To implement these functions, the SDT recommends either a combined LWS data and modeling environment or separate data and modeling environments be established. In order to use resources most effectively, TR&T should utilize existing facilities to the maximum extent possible, including those supported by other government agencies.

5.7 Transferring Research Products to Users

Space Weather Products

Successful transfer of research products to operational users requires close collaboration among NASA, NOAA, the DoD, and industry. Because of the LWS research focus on areas of high potential utility, it is expected that some specific model and data products will be developed that could later be tailored for use in industry and government activities. The key mechanisms that will facilitate the transfer of research products are the ready access to models and data (including in some cases real-time access to data from LWS missions) and the availability of verification studies and complete documentation for model use.

Models and tools to be transitioned from research to operations need to be robust and scientifically valid, and they need to be evaluated in a standardized fashion through agreed-upon metrics procedures (see Sections 5.3 and 5.5). Such science-based validation and metrics activities are also essential to assess overall program success and to track the development of overall capability. These evaluations should be performed by an unbiased entity that does not have a stake in the performance of any specific model undergoing testing. Source codes for transitioned models, with documentation and some tailored derivatives, should be available to the space weather operations centers.

Models to be transitioned to operations should be broadly available and usable by non-experts. TR&T funding should be made available for independent research and validation efforts using these models. Scientific studies that use the models will provide the best means to assess the accuracy, robustness and usability of the models.

Feedback from the user community should be solicited annually through mechanisms decided by the TSC. This feedback should be used to help determine the highest priority needs, evaluate the efficiency of model and data access, determine the value of the model verification, and determine the value of the models themselves. Users should also be solicited for suggestions of metrics that could

be applied. Where possible, researchers should be encouraged to apply metrics that have both scientific and operational value.

A recent report from the National Academy of Sciences Space Studies Board recommended that an interagency transition office should be established for planning and coordination of NASA and NOAA activities in support of transitioning research to design and operations, and should report to the highest levels of NASA and NOAA. By analogy, such coordination is also desirable in principal between NASA and the DoD. Assuming that an interagency transition office will be formed, it is recommended that LWS personnel participate in its formation and ongoing activities to ensure that coordination occurs between the LWS research community and the user community.

Sun-Climate/Ozone Modeling and Data Products

The research supported by TR&T is expected to increase our knowledge of the magnitude of the influence of solar variability on climate and ozone. Publication of the results of these studies in the open literature is anticipated, as are periodic reports to NASA Program Managers. The latest understanding regarding Sun-climate/ozone influences should be provided to the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization's Global Ozone Research and Monitoring Project (WMOGORMP) for use in future international assessments on climate and ozone change. The TR&T Program or Project Office should appoint a representative (a staff member or interested TR&T research participant) with the responsibility for passing along relevant research results periodically to IPCC and WMOGORMP. This will help ensure a strong linkage between the Sun-climate/ozone research program sponsored through TR&T with the international assessment organizations and lead to a wider dissemination of these research results.

6.0 APPENDIX

6.1 Acronyms

AFOSR: Air Force Office of Scientific Research
AFRL: Air Force Research Laboratory
AO: Announcement of Opportunity
APL: Applied Physics Laboratory (Johns Hopkins University)
CA: Cooperative Agreement
CCMC: Community Coordinated Modeling Center
CCRI: Climate Change Research Initiative
CEDAR: Coupling, Energetics and Dynamics of Atmospheric Regions
CISM: Center for Integrated Space Weather Modeling
CME: Coronal mass ejection
C/NOFS: Communication/Navigation Outage Forecast System
COSMIC: Constellation Observing System for Meteorology, Ionosphere, and Climate
DAAC: Distributed Active Archive Centers
DMSP: Defense Meteorological Satellite Program
DoD: Department of Defense
DoE: Department of Energy
DoI: Department of the Interior
DoT: Department of Transportation
ENSO: El Nino Southern (Ocean) Oscillation

EPA: Environmental Protection Agency
eV: Electron volt
EUV: Extreme Ultraviolet
GEM: Geospace Environment Modeling
GeV: Billion electron volts
GIC: Geomagnetically-induced currents
GSFC: Goddard Space Flight Center
HAO: High Altitude Observatory
HF: High frequency
HQ: Headquarters
IMF: Interplanetary magnetic field
IPCC: Intergovernmental Panel on Climate Change
IR: Infrared
LWS: Living With a Star
MO&DA: Mission Operations and Data Analysis
MOWG: Mission Operations Working Group
MURI: Multidisciplinary University Research Initiative
NASA: National Aeronautics and Space Administration
NAO: North Atlantic Oscillation
NCAR: National Center for Atmospheric Research
NGDC: National Geophysical Data Center
NIH: National Institute of Health
NOAA: National Oceanic and Atmospheric Administration
NPOESS: National Polar-orbiting Operational Environmental Satellite System
NRL: Naval Research Laboratory
NSF: National Science Foundation
NSSDC: National Space Science Data Center
NSWP: National Space Weather Program
OFCM: Office of the Federal Coordinator for Meteorology
ONR: Office of Naval Research
PI: Principal Investigator
RISE: Radiative Inputs of the Sun to Earth
R&A: Research and Analysis
RSTN: Radio Solar Telescope Network
SAT: Science Architecture Team
SDAC: Solar Data Analysis Center
SDO: Solar Dynamics Observatory
SDT: Science Definition Team
SEON: Solar Electro-Optical Network
SEP: Solar energetic particles
SEC: Sun-Earth Connections
SHINE: Solar, Heliosphere, and Interplanetary Environment
SOON: Solar Observing Optical Network
SPDF: Space Physics Data Facility
SuperDARN: Super Dual Auroral Radar Network
TMDA: Theory, Modeling and Data Analysis
TR&T: Targeted Research and Technology
TSC: Targeted Research and Technology Steering Committee

UAF: Upper Atmosphere Facilities (NSF)
UPOS: University Partnership for Operational Support
USAF: United States Air Force
USDA: United States Department of Agriculture
USGCRP: United States Global Change Research Program
USGS: United States Geological Survey
USN: United States Navy
UV: Ultraviolet
VIS: Visible
WMO: World Meteorological Organization
WMOGORMP: World Meteorological Organization's Global Ozone Research and Monitoring Project

6.2 Resources and Related Programs

The LWS TR&T program will proceed simultaneously with a variety of programs that explore the connected Sun-Earth system. The following provides a discussion of complementary programs fostered by NASA and other agencies. The breadth of these programs is testimony to the perceived relevance of research on space weather and solar influences on climate/ozone change. In addition to providing a new and substantial element of research and development, the TR&T mission will provide a central focus and a coordinating role for all activities addressing space weather and solar influences on climate/ozone change, whether or not formally under the LWS program.

6.2.1. Multi-Agency Programs and Facilities

The U.S. Global Change Research Program (USGCRP) and the Climate Change Research Initiative (CCRI) are intended to address key uncertainties about changes in the Earth's global environmental system, both natural and human-induced, to monitor, understand, and predict global change, and to provide a sound scientific basis for national and international decision-making. Participating US government agencies are: USDA, NOAA, DoD, DoE, NIH, USGS, EPA, NASA, NSF, and the Smithsonian Institution.

The National Space Weather Program (NSWP) emerged in 1994 from the efforts of several U.S. government agencies to prepare the country to deal with technological vulnerabilities associated with the space environment. Participating agencies include NSF, NASA, NOAA, USAF, USN, FAA, DoE, DoI and DoT. The goal of the National Space Weather Program (NSWP) is to mitigate the adverse effects of space weather. Emphasis is on understanding the fundamental physical processes that affect the state of the Sun, solar wind, magnetosphere, ionosphere, and upper atmosphere, focusing on answering research questions that will improve the ability to specify and predict conditions in the space environment. Through the Office of the Federal Coordinator for Meteorology (OFCM), these agencies documented the goals of that program in the *National Space Weather Program Strategic Plan* (FCM-P30-1995, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Silver Spring, MD, 1995). The interagency focus and cooperation continued with the development of the *National Space Weather Program Implementation Plan* (FCM-P31-1997, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Silver Spring, MD, 1997) in 1997 to provide more specific direction to the federal government's space weather efforts. In July 2000, the interagency consortium came out with the second edition of the *National Space Weather Program Implementation Plan* (FCM-P31-2000).

Within the NSWP, the Community Coordinated Modeling Center (CCMC) is a multi-agency partnership between NASA, NSF, USAF, USN, and NOAA. CCMC focuses on the transition of research models to operations and on community access to modern space science models. CCMC makes available a large number of research models and provides runs-on-request to the research community. CCMC also performs independent model evaluations based on metrics and science-based validations. CCMC presently occupies a dedicated facility at NASA's Goddard Space Flight Center.

6.2.2 NASA Sun-Earth Connections Programs and Facilities

Instrument Development
The program goal is to define and develop scientific instruments and/or components of such instruments. New measurement concepts may be proposed, as well as methods to provide significant improvements in the performance of existing instruments and/or the development of technologies that enable the packaging of multiple instruments in order to minimize the need for spacecraft resources.

Guest Investigator
The program goal is to maximize the return from currently operating missions by providing support for research of breadth and complexity beyond that of PI-funded investigations. Investigations proposed for this program element ideally use data from multiple spacecraft and carry out the associated interpretative data analysis, theory and modeling.

Theory
The program goal is to attack problems falling within the Sun-Earth Connection science theme that are of sufficient breadth that their successful completion requires the efforts of a synergistically interacting group of investigators. The program encourages the exploration and development of new areas in the SEC theme, especially those of interdisciplinary nature.

Solar and Heliospheric Physics
The program goal is to understand the origins of solar variability, its effects on the solar atmosphere and the heliosphere, and the transport and dissipation of matter and energy through the solar atmosphere to the outer edges of the heliosphere. This program supports investigations involving analyses of existing data, the development of computer programs that are or will be demonstrably available in the public domain, the development of theoretical models and numerical simulation techniques, the development or coordination of solar and heliospheric ground-based observing capabilities that support flight programs and, the exploration and demonstration of concepts for new instruments for future flight opportunities.

Geospace Sciences
The program goal is to understand the region of space that surrounds and is influenced by the Earth and its magnetic field, beginning with the investigation of the neutral upper atmosphere, including the mesosphere and thermosphere, and extending outwards through the ionosphere, into and beyond the magnetosphere. This program also supports studies of similar phenomena and processes at other solar system bodies.

Earth Science
Earth Science programs support research that address key questions including: What are the primary forcings of the Earth system, and especially, what trends in atmospheric constituents and solar radiation are driving global climate?

Facilities

NASA data centers include the National Space Science Data Center (NSSDC), the Solar Data Analysis Center (SDAC), the Space Physics Data Facility (SPDF), and the Earth Science Distributed Active Archive Centers (DAAC). NASA also operates the Solar Data Analysis Center (SDAC) at NASA's Goddard Space Flight Center, which brings together at one site a large collection of solar physics data sources.

6.2.3 Department of Defense Programs and Facilities

The DoD partners with the NSF by providing funding for research in support of the National Space Weather Program, and with NASA in supporting the Community Coordinated Modeling Center at Goddard Space Flight Center. Through the Office of Naval Research (ONR) and the Air Force Office of Scientific Research (AFOSR), the DoD supports basic research in space physics under various Broad Area Announcements. The DoD also maintains space weather expertise in applied research and development at its Naval Research Laboratory (NRL) and Air Force Research Laboratory (AFRL). To emphasize the importance of space weather to Air Force operations, AFRL maintains a Space Weather Center of Excellence at Hanscom Air Force Base near Boston, Massachusetts, as well as a liaison officer at the Air Force's space weather Rapid Prototyping Center in Colorado Springs, Colorado. In addition, the Air Force operates a worldwide system of ground based space weather observation sites, known as the Solar Electro-Optical Network (SEON), specializing in observations of the Sun and the ionosphere. The USAF supports the Solar Observing Optical Network (SOON) with five observing sites across the globe, and the Radio Solar Telescope Network (RSTN) with four sites worldwide. The Air Force also supports the transition of research findings to operational terrestrial and space weather products under the University Partnership for Operational Support (UPOS).

Presently, the DoD supports three major space weather science investigations under the Multidisciplinary University Research Initiative (MURI), each creating a multi-university consortium. MURI projects are funded for five years at levels approaching $1M annually. The MURI program supports basic science and engineering research of critical importance to national defense, focusing on multidisciplinary research efforts that intersect more than one traditional science and engineering discipline. By supporting multidisciplinary teams, these MURIs are complementary to the ongoing DoD space weather programs at AFOSR and ONR that support university research through single-investigator awards.

AFOSR and ONR have also been involved in other targeted technical collaborations, such as the National Security Space Architect's Space Weather Architecture Study, the joint US-Taiwan COSMIC satellite program, the triennial Ionospheric Effects Symposium, and the development of new space weather forecasting techniques at NOAA's Space Environment Center in Boulder, Colorado. The DoD also collaborates with NOAA in the development of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). NPOESS will replace the Defense Meteorological Satellite Program (DMSP), which for 30 years has provided the majority of ionospheric data for space weather needs. AFRL and ONR are collaborating with NASA in the development of the Communication/Navigation Outage Forecast System (C/NOFS) satellite, scheduled for launch in 2004 to study and forecast ionospheric scintillation.

6.2.4 NSF Programs and Facilities

NSF supports research in support of the National Space Weather Program (NSWP) and in addition supports related space physics research programs in Aeronomy, Magnetospheric Physics, and Solar-Terrestrial Physics. Special NSF research programs within these broad space physics programs

include Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR), Geospace Environment Modeling (GEM), Radiative Inputs of the Sun to Earth (RISE), and Solar and Heliospheric Interplanetary Environment (SHINE). Presently it supports the Center for Integrated Space Weather Modeling (CISM) under the NSF Science and Technology Centers program. There are climate change and variability programs in the Directorate for Geosciences, and other related research programs in astronomy and space physics in the Directorate of Mathematics and Physical Sciences.

In addition to the basic research programs, NSF supports a variety of ground-based observing facilities of relevance to the LWS program. These include the radars supported by the Upper Atmosphere Facilities (UAF) program. The UAF facilities are the incoherent scatter radars (Jicamarca, Peru; Arecibo, Puerto Rico; Millstone Hill, Massachusetts; Sondre Stromfjord, Greenland) and the Super Dual Auroral Radar Network (SuperDARN). NSF also supports the National Solar Observatory and the National Radio Astronomy Observatory. In addition, NSF supports the National Center for Atmospheric Research (NCAR), including the High Altitude Observatory (HAO).

6.2.5 NOAA Facilities

NOAA operates numerous environmental spacecraft, the National Geophysical Data Center (NGDC), and a real-time Space Weather Operations Center in partnership with the DoD. NOAA's Space Environment Center provides real-time alerts and warnings of space environment conditions, and makes available in real-time a variety of space environment data, such as solar X-ray images, disk-integrated X-ray flux, solar wind conditions, geosynchronous magnetic field and energetic particles, and low-altitude energetic particles. Numerous operational space environment models are also executed, and their output is made available in real time. The Space Environment Center also supports a Rapid Prototyping Center to expedite testing and transitioning of new models and data into operational use.

6.2.6 Space Assets

Data relevant to the TR&T program are available from a very large number of past, present and future space missions, including those sponsored by other NASA programs (both Code S and Code Y), other U.S. government agencies and other countries. The SDT has not attempted to identify those data sets most useful to the TR&T mission, but recommends that the LWS MOWG in conjunction with the TSC identify those key, non-LWS data sets that need to be integrated into the LWS data system.

6.3 Selected Statements from the LWS Science Architecture Team Report Relative to TR&T

- "LWS … has the unique feature that the questions to be addressed must be relevant to societal consequences."
- "Near-term progress must necessarily be based largely on theories, models, and observations of the type available today. Therefore, the near-term strategy for achieving progress is to improve on our current understanding and theories, as well as the observations."

- "The LWS program will need to develop large-scale global models well beyond the scale undertaken by individual Principal Investigators, and involving interfaces among traditional SEC regimes that are not the focus of existing research."
- "Modeling and theoretical efforts need to emphasize the coupled nature of the system."
- "In addition to traditional focused grants, an additional component of the Theory, Modeling, & Data analysis is needed: development of end-to-end models for selected Sun-Earth linkages."
- "The Living With a Star program will be considered a success if and only if there are substantial improvements in theoretical understanding and modeling of each component of the Sun-heliosphere-geospace system, and in particular of the linkages between these components."
- "Models must be seamlessly linked and new ideas and new concepts injected so that the final product is a working end-to-end model or models accurately depicting the comprehensive knowledge generated by the Living With a Star program."
- "…nowhere is the success in meeting the management challenge more crucial for the ultimate success of LWS than it is for theory, modeling and data analysis."

6.4 Charge to the Science Definition Team

Understand the present:

- Review the science and user objectives, priorities and justifications defined by NASA HQ and the Science Architecture Team for LWS.
- Obtain an overview of other national theory, modeling, and data analysis programs devoted to space weather problems with the goal of determining how they relate to the LWS TR&T program.
- Assess/review current relevant modeling capabilities and their development potential with respect to the LWS program.
- Characterize the potential of targeted theory and data analysis tasks for furthering LWS goals.

Address the near term:

- Identify theory and modeling activities that potentially augment the LWS program for implementation in the near future using data products currently available.
- Identify strategies for the analysis of presently available data sets with potential for research relevant to LWS.
- Identify and prioritize (at the top level) goals and requirements for the TR&T program from both science and user objectives for the next 5 years.

Address the overarching TR&T program goals:

- Define theory and model development as well as data analysis priorities.
- Define model evaluation and validation procedures.
- Define data sets required for model input and validation.

- Generate objectives for targeted theory and data analysis tasks.
- Discuss and recommend (if appropriate) procedures or methods to transfer research models and research results to interagency partners concerned with operations (DoD, NSF, NOAA and NASA are primary partners; DoT, DoE, and one or two others are partners with less presence).
- Determine mechanisms to ensure access by the general research community to models developed as a part of the LWS program.

Address issues of infrastructure and program implementation:

- Work with the LWS Project to obtain cost analyses of the candidate program elements, and iterate until the model elements are consistent with the budget cost cap.
- Work with the LWS Project to develop strawman funding mechanisms, profiles, and timelines to support TR&T R&D aspects.
- Develop top-level milestones and development schedules.
- Recommend, if possible, a top-level management structure to assess program success.
- To the extent possible, identify the kinds of automatic data processing assets likely required for program support.

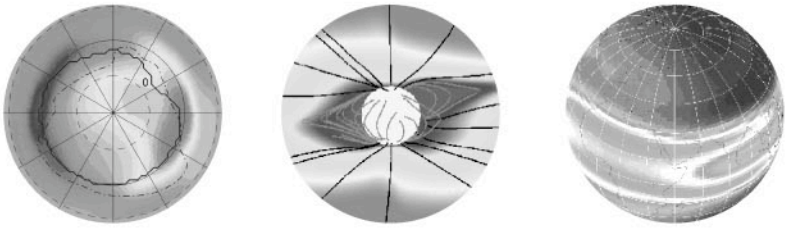
Definition of Success for the TRTSDT (Targeted Research and Technology Science Definition Team)

- The findings and recommendations of the TRTDT will allow the Code S management to devise an effective theory, modeling and data analysis implementation plan with explicit priorities that are in line with LWS goals and are achievable.

LWS Targeted Research and Technology

Science Definition Team Report

http://lws-trt.gsfc.nasa.gov



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